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SUBJECT Sandwich Composite – 3-point bending test for Composites with Rohacell & Fuzzy Carbon Cores		WRITTEN BY M. Wong		
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Summary

The BTeV beam pipe is a tube with an internal vacuum pressure. It must be made of material that minimizes secondary particle collisions. Many materials are considered, including thin aluminum, beryllium, and composites [1]. One option is a sandwich composite that is made up of two layers of aluminum foil with a lightweight core in between. This engineering note describes the three-point bending test performed on sandwich composite samples. The composites were constructed of a lightweight core sandwiched between thin aluminum foil. The assembly was held together using epoxy. The test results are compared to the theoretical values of the materials modulus of elasticity. Samples with a core of Rohacell foam are compared to samples with a core of fuzzy carbon, a proprietary material made by Energy Science Laboratories, Inc (ESLI). The sandwich composites that were tested were not as stiff as expected, for the modulus of elasticity was 44-60% of the calculated value. However, the thickness and modulus of elasticity are more than adequate as materials for a beam pipe so that the safety factor for buckling would be greater than four.

Material Description

Two types of sandwich composites where prepared for the test. One type of composite had skins made of aluminum foil of alloy 1145-O and 0.003-inch thickness. The core was made of Rohacell 31, a closed-cell polymethacrylimide rigid foam [2]. The Rohacell foam was 0.049 inch thick. The adhesive that was used to hold the layers together was Epon 815 with the AEP catalyst. The adhesive and catalyst were mixed at a ratio of 100:22 by weight. The mixture was then applied to the Rohacell foam using a roller to spread the mixture evenly. The aluminum foil was placed on each side of the foam. The composite was left overnight for the epoxy to cure under the weight of a lead brick. The panel dimensions were approximately 4x4x0.055 inches.

The other type of sandwich composite was made of aluminum skins and a fuzzy carbon core and was assembled by ESLI. The alloy of the aluminum was 5052-H19. The aluminum skins were 0.002-inch thick. The fuzzy carbon core was 0.106-inch thick. The amount of carbon in the core layer is 2.7% by volume. No information is available about the type of adhesive that was used to hold the layers together. However, total mass of the panel was 4.229 grams. The panel dimensions were approximately 3x4x0.108 inches.

In preparation for the test, the panels were cut into rectangular beams so that each piece was roughly 1 inch wide. Tables 1 and 2 show the dimension of each sample.

Table 1 – Dimensions of Rohacell Core Samples

Sample	Width (in.)	Depth (in.)	Cross-Sectional Area (in^2)
1	0.9980	0.0550	0.0549
2	1.0330	0.0555	0.0573
3	1.0660	0.0535	0.0570
4	1.0500	0.0550	0.0578

Table 2 – Dimensions of Fuzzy Carbon Core Samples

Sample	Width (in.)	Depth (in.)	Cross-Sectional Area (in^2)
1	1.024	0.108	0.111
2	1.006	0.108	0.109
3	0.991	0.108	0.107

Table 3 lists the average mass of the assembled sample and of its components in grams.

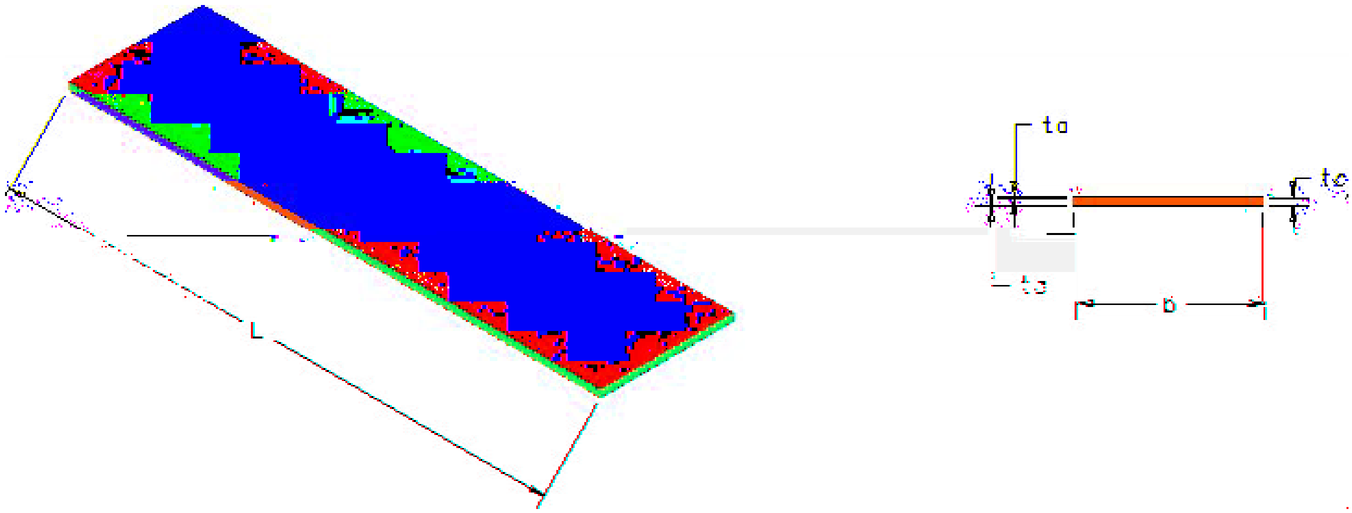
Table 3 – Average Mass of 1-inch Wide Samples in Grams

	Rohacell sandwich composite	Fuzzy Carbon sandwich composite
Mass of assembly	2.73	1.41
Total mass of aluminum skins	1.06	0.71
Combined mass of core & epoxy	1.67	0.71
Mass of core	0.10	--
Mass of epoxy	1.57	--

Theoretical Values

In analyzing the mechanical properties of a sandwich composite, the assumption is made that the core material provides no stiffness axially nor in bending. The core simply acts as the means to keep the skins of the sandwich composite a constant distance apart. To calculate the modulus of elasticity of the composite material, it is assumed that an equivalent beam of the same Poisson ratio, length and width exists. The value of the equivalent beam's thickness and modulus of elasticity would make the beam mechanically act the same as the sandwich composite. Using the definition of bending stiffness and extensional stiffness of a beam, the thickness and modulus of elasticity of a mechanically equivalent beam can be calculated.

Let the variables of the sandwich composite be defined as shown in Figure 1:



where: L = length (inch)
t_a = skin thickness (inch)
t_c = core thickness (inch)
b = width (inch)

Figure 1 – Variable Definition of Composite Beam

The total thickness of the material $t = 2t_a + t_c$.

As mentioned before, assume there exists a beam with the same length and width as the sandwich composite. The beam has the same mechanical properties as the sandwich composite. To calculate the equivalent thickness and modulus of elasticity of the beam, the definitions of bending stiffness and extensional stiffness are used. The bending stiffness, or the flexural rigidity, of a beam is defined as the product of the modulus of elasticity and the moment of inertia [3]. For a sandwich composite and its equivalent beam, let the following equation be defined:

$$E * I = \frac{E * b * (t^3 - t_c^3)}{12 * (1 - \upsilon^2)} = \frac{E_e * b * t_e^3}{12 * (1 - \upsilon^2)} \quad (1)$$

where: E = modulus of elasticity for aluminum (psi)
υ = Poisson's ration for aluminum
E_e = modulus of elasticity for equivalent beam (psi)
t_e = thickness of equivalent beam (inch)

To solve for the value of the equivalent beam's modulus of elasticity E_e, the definition of stress in a beam is used:

$$\sigma = E * \varepsilon \quad (2)$$

where: σ = stress
E = modulus of elasticity
ε = strain = x/L
L = original beam length
x = deflection in beam due to axial force

Multiplying both sides of the equation by the value A = cross section of the beam:

$$F = E*\varepsilon*A \tag{3}$$

where: F = axial force = σ*A

Multiplying the right side of the equation by (L/L):

$$F = E*A*(\frac{\varepsilon * L}{L})$$
$$F = \frac{E*A}{L}*x \tag{4}$$

With the definition of force in terms of its spring constant, or the extensional stiffness:

$$F = k*x \tag{5}$$

where: F = axial force
k = spring constant = extensional stiffness
x = deflection due to axial force

the extensional stiffness k is defined as:

$$k = \frac{E*A}{L} \tag{6}$$

The extensional stiffness is then written in terms of the variables defining the sandwich composite and its equivalent beam:

$$k = \frac{E*b*(t-t_c)}{1-\upsilon} = \frac{E_e*b*t_e}{1-\upsilon} \tag{7}$$

Solving for the beam's equivalent modulus of elasticity E_e:

$$E_e = \frac{t-t_c}{t_e}*E \tag{8}$$

Solving for the beam's thickness t_e requires dividing the values of the bending stiffness by the extensional stiffness:

$$\frac{E*I}{k}=\frac{\left(\frac{E*b*(t^3-t_c^3)}{12*(1-\upsilon^2)}\right)}{\left(\frac{E*(t-t_c)}{(1-\upsilon^2)}\right)}=\frac{\left(\frac{E_e*b*t_e^3}{12*(1-\upsilon^2)}\right)}{\left(\frac{E_e*t_e}{(1-\upsilon^2)}\right)} \tag{9}$$

$$t_e=\sqrt{\frac{t^3-t_c^3}{t-t_c}}$$

For the sandwich composites, the equivalent beams have the thickness and modulus of elasticity shown in Table 4.

Table 4 – Equivalent Beam Thickness & Modulus of Elasticity

	Rohacell sandwich composite	Fuzzy Carbon sandwich composite
Skin thickness t_a (inch)	0.003	0.002
Core thickness t_c (inch)	0.049	0.104
Beam thickness t (inch)	0.055	0.108
Skin modulus of elasticity (psi)	1.00e7	1.00e7
Equivalent beam modulus of elasticity E_e (psi)	6.66e5	2.18e5
Equivalent beam thickness t_e (inch)	0.090	0.184

Using the equivalent modulus of elasticity and thickness, the maximum load and deflection of the beam can be calculated. For a beam this is simply supported at the ends and is loaded in a location midway between the supports, the maximum load and deflection are found:

$$P=\frac{4*M_{max}}{L} \qquad y_{max}=\frac{P*L^3}{48*E_e*I}$$

$$P=\frac{4*\sigma_{max}*I}{L*c} \tag{10,11}$$

$$P=\frac{4*\sigma_{max}*b*t_e^3}{L*c*12} \qquad y_{max}=\frac{P*L^3*12}{48*E_e*b*t_e^3}$$

where: P = maximum load on beam (lb)
M_{max} = maximum bending moment (in-lb)
L = distance between supports = 2 inch
σ_{max} = maximum stress in beam = 4,000 psi (yield stress of aluminum skin – alloy 1145-O)
I = moment of inertia (in^4)
c = distance from outer edge of cross section to neutral axis = 0.5*t_e
y_{max} = maximum displacement (inch)

Test Procedure

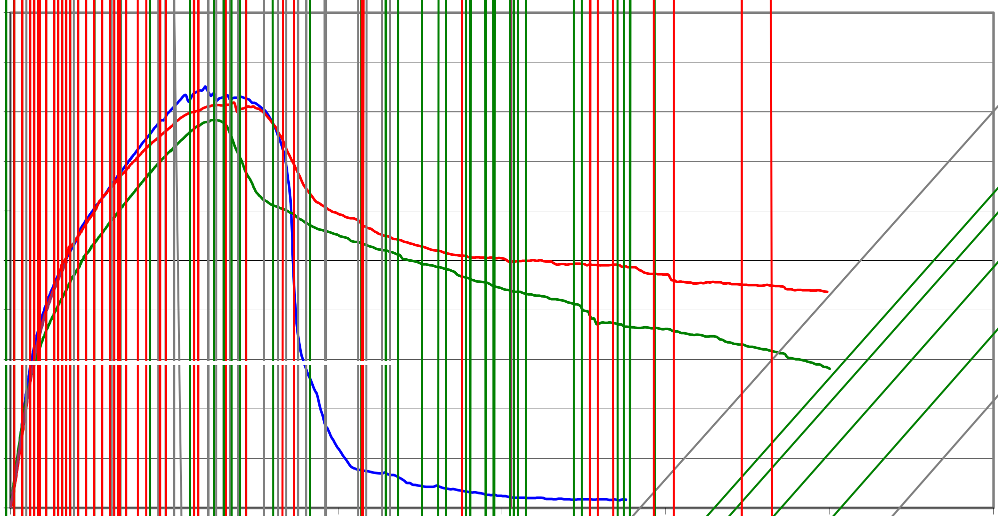
A three-point bending test was performed on each sample. The test setup is shown in Figures 2 and 3. A test fixture was attached to an Instron machine. The fixture had supports that were 2 inches apart. The load was placed midway between the supports. The force per sample width and deflection were recorded on a computer. Each sample was loaded until the core broke.

Figure 2 – Text Fixture Set Up in Instron Machine

Figure 3 – Text Fixture with Sample

Test Results

Figure 4 shows the force versus displacement of each Rohacell composite sample during the test.



All data was shifted so that the initial force and displacement were zero.

For the Rohacell composite, the initial slope in the force-deflection curves is likely to represent the panels being loaded elastically without any changes in the structure. The sample likely yielded when at the point where the straight line ends and the curved line begins. For all samples, the yield load was close to 1.25 pounds. The curve between the initial slope and the peak load is likely to represent the compression of the core material as the load increases. The peak load takes place when the core and/or aluminum skin break. In two of the samples, the aluminum skins stayed in tact and the core was broken. In the other two samples, both the skin and the core failed. Table 4 lists the test values of the deflection and load at failure.

Table 4 – Maximum Load and Deflection at Failure for the Rohacell Composite

Sample	Max. Load (lb)	Max. Displacement (in)
1	4.25	0.119
2	4.09	0.138
3	3.91	0.126
4	4.48	0.126
Average	4.18	0.127

For the fuzzy carbon samples, the force-deflection curves show a more catastrophic failure without a clear yield point. For all samples, at the peak load the aluminum was still intact. Only the core had failed. Table 5 lists the load and deflection at failure.

Table 5 – Maximum Load and Deflection at Failure for the Fuzzy Carbon Composite

Sample	Max. Load (lb)	Max Displacement (in)
1	8.95	0.030
2	7.59	0.029
3	6.99	0.027
Average	7.84	0.029

The modulus of elasticity for each piece was calculated using the measured load and deflection at yield. Table 6 shows the modulus of elasticity and the loads and deflections used. The theoretical modulus of elasticity is shown for comparison. It is assumed that the samples had an equivalent thickness t_e that was calculated using equation 9. To determine the modulus of elasticity, equation 11 was used.

Table 6 – Theoretical and Tested Modulus of Elasticity

Sample Number	Rohacell Composite	Fuzzy Carbon Composite
1	329,718	149,684
2	273,817	123,420
3	283,942	118,658
4	278,826	--
Average	291,576	130,587
Theoretical	665,800	217,855